

THE COSMIC MeV GAMMA-RAY BACKGROUND AND HARD X-RAY SPECTRA OF ACTIVE GALACTIC NUCLEI: IMPLICATIONS FOR THE ORIGIN OF HOT AGN CORONAE

YOSHIYUKI INOUE, TOMONORI TOTANI, AND YOSHIHIRO UEDA

Department of Astronomy, Kyoto University, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan

Draft version February 2, 2008

ABSTRACT

The origin of the extragalactic gamma-ray background radiation at 1–10 MeV is still unknown. Although the cosmic X-ray background (CXB) up to a few hundreds keV can be accounted for by the sum of Active Galactic Nuclei (AGNs), current models of AGN spectra cannot explain the background spectrum beyond ~ 1 MeV, because of the thermal exponential cutoff of electron energy distribution assumed in the models. Here we construct a new spectral model by calculating the Comptonization process including nonthermal electrons, which are expected to exist in an AGN hot corona if it is heated by magnetic reconnections. We show that the MeV background spectrum can nicely be explained by our model, when coronal electrons have a nonthermal power-law component whose total energy is a few percent of the thermal component and whose spectral index is $d \ln N_e / d \ln E_e \approx -4$. Although the MeV gamma-ray flux from such a component in nearby AGN spectra is below the detection limit of past observations, it could be detected by planned future MeV detectors. We point out that the amount of the nonthermal component and its electron index are similar to those found for electrons accelerated by magnetic reconnections in solar flares and the Earth magnetosphere, giving a support to the reconnection hypothesis for the origin of hot AGN coronae.

Subject headings: diffuse radiation — galaxies: active — gamma rays: theory

1. INTRODUCTION

It is well-known that normal active galactic nuclei (AGNs) explain the cosmic X-ray background (CXB) below several hundreds keV (for reviews see Boldt 1987; Fabian & Barcons 1992; Ueda et al. 2003, hereafter U03; Gilli, Comastri, & Hasinger 2007). It is also known that rare AGNs of the blazar type make a considerable contribution to the cosmic gamma-ray background in the energy range from 100 MeV to 100 GeV, which has a hard power-law spectrum (almost flat in the νF_ν plot), though blazars may not explain all of the background flux, leaving some room for possible contributions from completely different sources (Narumoto & Totani 2006, and references therein).

The origin of the gamma-ray background at the gap between these two energy regions, i.e., ~ 1 –10 MeV, has also been an intriguing mystery. The AGN spectra adopted in population synthesis models of the CXB cannot explain this component because of the assumed exponential cut-off at a few hundred keV. The background spectrum in the 1–10 MeV band is much softer (photon index $\alpha \sim 2.8$) than the GeV component, indicating a different origin from that above 100 MeV (e.g. Sreekumar et al. 1998).

A few candidates have been proposed to explain the 1–10 MeV background. One is the nuclear decay gamma-rays from type Ia supernovae (SNe Ia) (Clayton & Ward 1975; Zdziarski 1996; Watanabe et al. 1999). However, recent studies based on the latest measurements of the cosmic SN Ia rates show that the background flux expected from SNe Ia is about an order of magnitude lower than observed (Ahn, Komatsu, & Höflich 2005; Strigari et al. 2005). There is a class of blazars called “MeV blazars”, whose spectra have peaks at \sim MeV (Blom et al. 1995; Sambruna et al. 2006), and these MeV

blazars could potentially contribute to the MeV background. However, quantitative estimate of the contribution is difficult because of the still small sample available at present. Annihilation of the dark matter particles has also been discussed (Ahn & Komatsu 2005a, 2005b; Ramera et al. 2006; Lawson & Zhitnitsky 2007), but there is no natural particle physics candidate for such a dark matter particle with a mass scale of \sim MeV. The motivation of MeV dark matter has been inspired by the 511 keV line emission from the Galactic center, but a few astrophysical explanations are possible for this line emission (Totani 2006, and references therein).

An important feature of the MeV background spectrum is that its power-law spectrum is *smoothly* connected to the peak of the CXB spectrum. If the origin of the MeV background is completely different from that of the CXB, such a smooth connection would be surprising. Rather, it seems more plausible that the MeV background flux is composed of the same populations that make the CXB, and simply the current AGN spectral models are not sufficient to describe the MeV spectra. The X-ray AGN spectra are well described by the Comptonization of seed UV photons by the hot coronal electrons (Zdziarski et al. 1994, 1995), and the cut-off at ~ 100 keV reflects the thermal energy distribution of the hot electrons. Although the AGN spectra indeed show evidence for such a cut-off (Zdziarski et al. 1995; Zdziarski, Poutanen, & Johnson 2000), a small amount of additional non-thermal electrons with a soft spectrum is sufficient to explain the MeV background. Due to the limited sensitivity of current MeV gamma-ray observations, the presence of such non-thermal components is not strongly constrained even in the spectra of nearby brightest AGNs. Furthermore, it is believed that coronae around accretion disks share some common features with the solar corona (e.g., Galeev, Rosner, & Vaiana

1979), and magnetic reconnection in AGN coronae is a good candidate for the origin of hot electrons (Liu, Mineshige, & Shibata 2002). It is well known that particles are accelerated to nonthermal energies by reconnections in solar flares (Shibata et al. 1995).

Here we construct a new model of the X/gamma-ray spectra of AGNs, by calculating the Comptonization process by hot electrons having both thermal and nonthermal components. We also calculate the CXB spectrum based on our model with the latest knowledge of the cosmological evolution of the AGN luminosity function, and determine the amount and spectrum of the nonthermal electrons in AGN coronae to explain the MeV background. We discuss the implied nature of nonthermal electrons in the context of the reconnection heating scenario of the AGN coronae, comparing our results with those found in the reconnections occurring in the solar flares and the Earth magnetosphere.

Rogers & Field (1991) and Field & Rogers (1993) presented an AGN spectral model that can explain the MeV background spectrum by nonthermal relativistic electrons. However, their model only considers the nonthermal component without a thermal component, and it requires a *lower* cut-off of $\gamma_e \sim 30$ in the nonthermal component, which is difficult to interpret as they mentioned in their paper. Our model considers both the thermal and nonthermal coronal electrons whose spectra are smoothly connected to each other, which is a natural extension of the popular AGN spectral models in the recent literature. Stecker, Salamon, & Done (1999) also discussed a possibility that the MeV background is explained by nonthermal tails in AGN spectra, quoting the spectrum of the Galactic stellar-mass black hole candidate Cyg X-1. However, a physical model to explain the nonthermal tail in an AGN spectrum was not presented.

Throughout this paper, we adopt the cosmological parameters of $(h_0, \Omega_m, \Omega_\lambda) = (0.7, 0.3, 0.7)$.

2. MODEL DESCRIPTION

2.1. the AGN Spectra with Nonthermal Coronal Electrons

The main shape of X-ray AGN spectra is determined by Comptonization of UV photons emitted from optically-thick accretion disks by hot electrons in coronae. As in many previous studies, we consider a simple spherical and uniform distribution of the coronal electrons. The seed UV photons are injected at the center and then become X-ray photons when they escape the coronal region after Comptonization. In addition to the hot thermal electrons assumed in the conventional X-ray spectral models of AGNs, we introduce higher energy nonthermal electrons in AGN coronae, whose energy distribution is a power-law as $dN_e/dE_e \propto E_e^{-\Gamma}$. We introduce the transition electron Lorentz factor γ_{tr} , corresponding to the transition electron energy $E_e = m_e \gamma_{tr}$ where the electron spectrum dN_e/dE_e has the same value for the thermal and nonthermal components. This γ_{tr} is the lower limit of the Lorentz factor distribution of the nonthermal component, and hence there are no nonthermal electrons at $E_e < m_e \gamma_{tr}$. We also set an upper bound as $\gamma_u = 10^5$, although this hardly affects our results if the maximum photon energy well extends beyond 10 MeV.

We set the coronal temperature to be $kT_e = 256$ keV and assume a blackbody spectrum for UV seed photons

from a cooler disk with $T_d = 10$ eV, following the conventional thermal models (e.g. Zdziarski et al. 1994). The degree of Comptonization is determined by the optical depth for Thomson scattering, τ_T . We found that the spectral photon index in the X-ray band, α_X , becomes close to that typically found in observed spectra ($\alpha_X \approx 1.9$, e.g., Nandra & Pounds 1994; Turner et al. 1997; George et al. 1998) when we set $\tau_T = 0.24$. Therefore we use this value throughout this letter; this value is also similar to those used in the conventional models. It should be noted that α_X is hardly changed even if we introduce the nonthermal electron component with an amount that is necessary to explain the cosmic MeV background.

We then trace the Comptonization process using a Monte Carlo method. The calculation method used here is mainly based on that in Pozdniakov, Sobol, & Siuniae (1977) and Gorecki & Wilczewski (1984), but their original formalism in the laboratory frame is not optimized for the ultra-relativistic region. To calculate the scattering by high energy nonthermal electrons more efficiently, we added a new formulation in the rest frame of relativistic electrons based on Corman (1970).

The reflection of X-ray photons by cool, optically thick matter is also an important feature of AGN X-ray spectra. We calculate this by using the PEXRAV model (Magdziarz & Zdziarski 1995) in the XSPEC package as done in U03. Because of the limitation for the acceptable input spectrum in PEXRAV, we use a power-law spectrum ($\alpha_X = 1.9$) plus an exponential cutoff at $E = 500$ keV, which is a good approximation of the Comptonized spectrum only with the thermal electrons. The newly added nonthermal electrons would change the spectrum significantly only at $E \gtrsim 1$ MeV, and hence this treatment is appropriate for the reflection component which is important only at ~ 1 –100 keV.

2.2. Calculation of the Cosmic Background Radiation

We calculate the CXB spectrum by integrating our AGN spectral model in the redshift and luminosity space, using the X-ray AGN luminosity function of U03. Following the same formulation given in U03, we take into account the absorption column density distribution (N_H function) and the contribution from Compton-thick AGNs. We confirm that our main conclusion hardly change if instead we use a more recent population synthesis model by Gilli et al. (2007), as described below.

3. RESULTS

Figure 1 shows the models of AGN spectra calculated according to the procedures in the previous section. Here, we do not take into account the reflection component and the absorption effect, to show the pure spectrum of the Comptonization. We set $\Gamma = 3.8$ and $\gamma_{tr} = 4.4$ as our standard model (solid line), because we will find that these values give the best-fit MeV background spectrum to the data. In this standard model, 3.5% of the total electron energy is carried by the nonthermal electrons. To illustrate effects of changing parameters, we also show the spectra with parameters slightly changed from those for the best fit model. The conventional case only with the thermal electrons is also shown, where an exponential cutoff above ~ 100 keV is seen as expected.

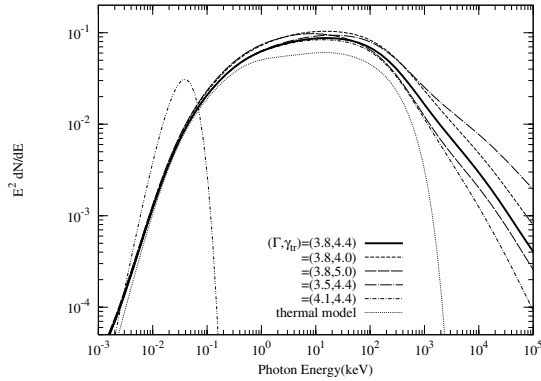


FIG. 1.— The AGN spectra in X-ray and gamma-ray bands calculated by our model. The flux is shown in an arbitrary unit of $E^2 dN/dE$, where dN/dE is a differential photon spectrum. They are Comptonization of UV seed photons without taking into account the reflection component and the absorption effect. The thick solid curve is our standard spectrum with $\Gamma = 3.8$ and $\gamma_{tr} = 4.4$. The other thick curves are for the cases of different model parameters as indicated in the figure. The thick dotted curve is the spectrum only with the thermal component ($kT_e = 256$ keV). The thin dotted curve is the input UV spectrum (a black body with $T_d = 10$ eV).

Figure 2 shows the cosmic background radiation integrated with the luminosity function of U03 using our AGN spectral model. It has been known that the predicted CXB spectrum below 100 keV by the U03 model is 10–20% higher than the HEAO-1 data. The origins of this discrepancy are still controversial. The intensity and shape of the CXB in the 10 keV – 1 MeV band could be uncertain at $\approx 20\%$ level¹. The population synthesis models have also uncertainties, such as the intensity of the reflection component assumed in the AGN spectra, the (unknown) number density of Compton-thick AGNs, and the parameters of the luminosity function itself that could be subject to cosmic variance in deep surveys. However, here we emphasize that the uncertainty hardly affects our conclusions. To confirm this, we also calculate the MeV gamma-ray background flux with the U03 luminosity function by artificially lowering its normalization by 20% to match the HEAO-1 data. We find that the best fit value of γ_{tr} is slightly changed by 0.4, while the change of Γ is negligible.

As mentioned above, we find here that the cosmic background spectrum from X-ray to 10 MeV band can nicely be explained by our model with $\Gamma = 3.8$ and $\gamma_{tr} = 4.4$. The next question is then how natural are these parameters in the context of the theoretical picture of hot electrons in AGN coronae. We will discuss about this issue in the next section.

4. DISCUSSIONS

4.1. Reconnection and Nonthermal Electrons

As discussed in §1, magnetic reconnection is the primary candidate for the origin of the nonthermal electrons in AGN coronae, and we can compare the inferred amount and spectrum of electrons with those observed in

¹ In Figure 2, a discontinuity is seen between the HEAO-1 A4 MED data above 100 keV and the HEAO-1 A4 LED data below 100 keV (Gruber et al. 1999, see also ; Revnivtsev et al. 2005; Churazov et al. 2007; Frontera et al. 2007). If we use the model by Gilli et al. (2007), the discrepancy is reduced below 100 keV but is enhanced above 100 keV.

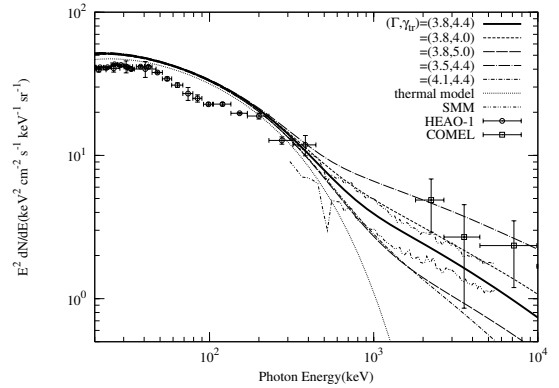


FIG. 2.— The spectrum of the cosmic background radiation in X-ray and gamma-ray bands, predicted by our model of AGN spectra shown in Fig. 1. For each line-marking, the corresponding AGN spectrum in Fig. 1 is used for the calculation. The data points of HEAO-1 (Gruber et al. 1999) SMM (Watanabe et al. 1999), and COMPTEL (Kappadath et al. 1996) experiments are also shown. For the SMM data the thin dotted line indicates the $\pm 1\sigma$ uncertainty region.

reconnections in other objects. In solar flares, the electron spectrum accelerated by reconnection and injected into the solar surface (foot points) can be estimated by thick-target bremsstrahlung (Brown 1971; Piana 1994), and a value of $\Gamma \sim 4$ is inferred for giant solar flares (Holman et al. 2003; Lin 2006). In the reconnection diffusion region of the Earth’s magnetotail, $\Gamma = 3.8$ has been measured by the Wind spacecraft (Øieroset et al. 2002). Interestingly, these values are very similar to what we found to explain the MeV background spectrum by AGNs.

The relative amounts of the thermal and nonthermal electrons are difficult to predict, but it should be determined by the balance between the cooling of the thermal electrons, thermalization of nonthermal electrons, and energy input rate by reconnections. In solar flares, the total energy of accumulated nonthermal electrons is comparable with or even larger than that of the thermal electrons (Holman et al. 2003). In the directly observed electron spectrum in the Earth’s magnetotail, the non-thermal component is smoothly connected to the thermal component at the energy where the thermal electron spectrum declines by the exponential cutoff, which is reminiscent of the cosmic background spectrum from X-ray to the MeV band. Therefore, the inferred amount of nonthermal electrons in AGN coronae seems quite reasonable in comparison with the reconnections observed in the Sun or the Earth magnetosphere.

As in the solar flare, some of the nonthermal electrons in AGNs would be injected into accretion discs along the magnetic field lines, and would produce bremsstrahlung emission. Such emission may also contribute to the AGN spectra. However, we consider here the inverse-Compton scattering since X-ray AGN spectra are well explained by the Comptonization process, indicating that the efficiency of Comptonization is much higher than bremsstrahlung in AGNs, in contrast to the case of X-ray radiation from solar flares. It should be noted that the radiation efficiency of the thick-target bremsstrahlung is generally much lower than the unity because the electrons injected into dense material would lose their energy by ionization or Coulomb losses rather than bremsstrahlung.

4.2. Implications for Future MeV Observations of AGNs

Our results suggest that the majority of AGN populations that are responsible for the CXB should commonly have a nonthermal component beyond the thermal exponential cutoff in their gamma-ray spectra. Future sensitive MeV observations may reveal the nonthermal components from nearby AGN spectra. For instance, the Advanced Compton Telescope (ACT, see Boggs (2006)), scheduled for launch around 2015, will have a continuum sensitivity in the 0.2–10 MeV band with $E_\gamma^2 dF_\gamma/dE_\gamma \sim 1 \times 10^{-5} (E_\gamma/\text{MeV}) \text{ MeV cm}^{-2}\text{s}^{-1}$, where dF_γ/dE_γ is the differential photon flux. Using the hard X-ray flux of NGC 4151 (Sazonov et al. 2007), the brightest Seyfert galaxy, we estimate the expected nonthermal MeV flux as $\sim 3 \times 10^{-5} (E_\gamma/\text{MeV})^{-0.8} \text{ MeV cm}^{-2}\text{s}^{-1}$, which can well be detected with the ACT. The detection of such components from nearby bright AGNs would give a clear test for our model.

5. CONCLUSIONS

In this paper, we have shown that MeV gamma-ray background can be explained by the same population of

AGNs that makes the CXB, by considering Comptonization by nonthermal electrons in AGN coronae that are theoretically expected to exist. The best fit to the MeV gamma-ray background is obtained when the nonthermal component has $\sim 3.5\%$ of the total electron energy with a spectrum of $dN_e/dE_e \propto E_e^{-3.8}$. This power law index is close to that of electrons accelerated by magnetic reconnections in solar flares or the Earth magnetosphere (Holman et al. 2003; Lin 2006; Øieroset et al. 2002). This gives a support to the idea of the reconnection-heated AGN corona (Liu et al. 2002). There is a chance for future MeV detectors with an improved sensitivity to directly detect the nonthermal component predicted by our model from nearby bright AGNs.

We would like to thank Eiichi Komatsu for useful discussions, and Duane Gruber and Ken Watanabe for providing their observational data. This work was supported by the Grant-in-Aid for the 21st Century COE "Center for Diversity and Universality in Physics" from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

REFERENCES

- Ahn, K. & Komatsu, E. 2005a, *Phys. Rev. D*, 71, 021303
—, 2005b, *Phys. Rev. D*, 72, 061301
Ahn, K., Komatsu, E., & Höflich, P. 2005, *Phys. Rev. D*, 71, 121301
Blom, J. J., et al. 1995, *A&A*, 298, L33+
Boggs, S. E. 2006, *New Astronomy Review*, 50, 604
Boldt, E. 1987, *Phys. Rep.*, 146, 215
Brown, J. C. 1971, *Sol. Phys.*, 18, 489
Churazov, E., et al. 2007, *A&A*, 467, 529
Clayton, D. D. & Ward, R. A. 1975, *ApJ*, 198, 241
Corman, E. G. 1970, *Phys. Rev. D*, 1, 2734
Fabian, A. C. & Barcons, X. 1992, *ARA&A*, 30, 429
Field, G. B. & Rogers, R. D. 1993, *ApJ*, 403, 94
Frontera, F., et al. 2007, *ApJ*, 666, 86
Galeev, A. A., Rosner, R., & Vaiana, G. S. 1979, *ApJ*, 229, 318
George, I. M., Turner, T. J., Netzer, H., Nandra, K., Mushotzky, R. F., & Yaqoob, T. 1998, *ApJS*, 114, 73
Gilli, R., Comastri, A., & Hasinger, G. 2007, *A&A*, 463, 79
Gorecki, A. & Wilczewski, W. 1984, *Acta Astronomica*, 34, 141
Gruber, D. E., Matteson, J. L., Peterson, L. E., & Jung, G. V. 1999, *ApJ*, 520, 124
Holman, G. D., Sui, L., Schwartz, R. A., & Emslie, A. G. 2003, *ApJ*, 595, L97
Kappadath, S. C., et al. 1996, *A&AS*, 120, C619+
Lawson, K. & Zhitnitsky, A. R. 2007, *ArXiv e-prints*, 704
Lin, R. P. 2006, *Space Science Reviews*, 124, 233
Liu, B. F., Mineshige, S., & Shibata, K. 2002, *ApJ*, 572, L173
Magdziarz, P. & Zdziarski, A. A. 1995, *MNRAS*, 273, 837
Nandra, K. & Pounds, K. A. 1994, *MNRAS*, 268, 405
Narumoto, T. & Totani, T. 2006, *ApJ*, 643, 81
Øieroset, M., Lin, R. P., Phan, T. D., Larson, D. E., & Bale, S. D. 2002, *Physical Review Letters*, 89, 195001
Piana, M. 1994, *A&A*, 288, 949
Pozdniakov, L. A., Sobol, I. M., & Siuniaev, R. A. 1977, *AZh*, 54, 1246
Rasera, Y., Teyssier, R., Sizun, P., Cassé, M., Fayet, P., Cordier, B., & Paul, J. 2006, *Phys. Rev. D*, 73, 103518
Revnivtsev, M., Gilfanov, M., Jahoda, K., & Sunyaev, R. 2005, *A&A*, 444, 381
Rogers, R. D. & Field, G. B. 1991, *ApJ*, 378, L17
Sambruna, R. M., et al. 2006, *ApJ*, 646, 23
Sazonov, S., Revnivtsev, M., Krivonos, R., Churazov, E., & Sunyaev, R. 2007, *A&A*, 462, 57
Shibata, K., Masuda, S., Shimojo, M., Hara, H., Yokoyama, T., Tsuneta, S., Kosugi, T., & Ogawara, Y. 1995, *ApJ*, 451, L83+
Sreekumar, P., et al. 1998, *ApJ*, 494, 523
Stecker, F. W., Salamon, M. H., & Done, C. 1999, *astro-ph/9912106*
Strigari, L. E., Beacom, J. F., Walker, T. P., & Zhang, P. 2005, *Journal of Cosmology and Astro-Particle Physics*, 4, 17
Totani, T. 2006, *PASJ*, 58, 965
Turner, T. J., George, I. M., Nandra, K., & Mushotzky, R. F. 1997, *ApJS*, 113, 23
Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, *ApJ*, 598, 886
Watanabe, K., Hartmann, D. H., Leising, M. D., & The, L.-S. 1999, *ApJ*, 516, 285
Zdziarski, A. A. 1996, *MNRAS*, 281, L9+
Zdziarski, A. A., Fabian, A. C., Nandra, K., Celotti, A., Rees, M. J., Done, C., Coppi, P. S., & Madejski, G. M. 1994, *MNRAS*, 269, L55+
Zdziarski, A. A., Johnson, W. N., Done, C., Smith, D., & McNaron-Brown, K. 1995, *ApJ*, 438, L63
Zdziarski, A. A., Poutanen, J., & Johnson, W. N. 2000, *ApJ*, 542, 703